

Scaling patterns for azimuthal anisotropy in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV: Further constraints on transport coefficients

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Azimuthal anisotropy measurements for charged hadrons, characterized by the second order Fourier coefficient v_2 , are used to investigate the path length (L) and transverse momentum (p_T) dependent jet quenching patterns of the QCD medium produced in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. v_2 shows a linear decrease as $1/\sqrt{p_T}$ and a linear increase with the medium path length difference (ΔL) in- and out of the Ψ_2 event plane. These patterns compliment a prior observation of the scaling of jet quenching (R_{AA}) measurements. Together, they suggest that radiative parton energy loss is a dominant mechanism for jet suppression, and v_2 stems from the difference in the parton propagation length ΔL . An estimate of the transport coefficient \hat{q} , gives a value comparable to that obtained in a prior study of the scaling properties of R_{AA} . These results suggest that high- p_T azimuthal anisotropy measurements provide strong constraints for delineating the mechanism(s) for parton energy loss, as well as for reliable extraction of \hat{q} .

Ultrarelativistic heavy ion collisions can produce a high energy-density plasma of quarks and gluons (QGP) [1]. Full characterization of the transport properties of this plasma, is a central objective of current research at both the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). A key ingredient for such a characterization is a full understanding of the mechanism by which hard scattered partons interact and lose energy in the QGP, prior to their fragmentation into topologically aligned high- p_T hadrons or jets [2]. This energy loss manifests as a suppression of hadron yields [3] – termed “jet quenching” – which depends on the momenta of the partons and the path length for their propagation through the QGP [2, 4–6].

Such a suppression is routinely quantified with the measured hadron yields in A+A and p+p collisions, via the nuclear modification factor (R_{AA}) [3, 7];

$$R_{AA}(p_T) = \frac{1/N_{\text{evt}} dN/dy dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dy dp_T}, \quad (1)$$

where σ_{pp} is the particle production cross section in p+p collisions and $\langle T_{AA} \rangle$ is the nuclear thickness function averaged over the impact parameter (\mathbf{b}) range associated with a given centrality selection

$$\langle T_{AA} \rangle \equiv \frac{\int T_{AA}(\mathbf{b}) d\mathbf{b}}{\int (1 - e^{-\sigma_{pp}^{inel} T_{AA}(\mathbf{b})}) d\mathbf{b}}. \quad (2)$$

The average number of nucleon-nucleon collisions, $\langle N_{coll} \rangle = \sigma_{pp}^{inel} \langle T_{AA} \rangle$, is usually obtained via a Monte-Carlo Glauber-based model calculation [8, 9]. Detailed measurements of the centrality and p_T dependence of R_{AA} are key to ongoing efforts to delineate the transport properties of the QGP produced in heavy ion collisions at both the LHC and RHIC [5, 6, 10–19].

Differential measurements of the azimuthal anisotropy of high- p_T hadrons also provide an indispensable probe to

study jet quenching. Here, the operational ansatz is that the partons which traverse the QGP medium in the direction parallel (perpendicular) to the event plane result in less (more) suppression due to the shorter (longer) parton propagation lengths [20–23]. The resulting anisotropy can be characterized via Fourier decomposition of the measured azimuthal distribution;

$$\frac{dN}{d\phi} \propto \left(1 + \sum_{n=1} 2 v_n \cos(n[\phi - \Psi_n]) \right), \quad (3)$$

where $v_n = \langle \cos(n[\phi - \Psi_n]) \rangle$, $n = 1, 2, 3, \dots$ and the Ψ_n are the generalized participant event planes at all orders for each event. Characterization can also be made via the pair-wise distribution in the azimuthal angle difference ($\Delta\phi = \phi_1 - \phi_2$) between particles [24–26];

$$\frac{dN_{\text{pairs}}}{d\Delta\phi} \propto \left(1 + \sum_{n=1} 2 v_n^a(p_T^a) v_n^b(p_T^b) \cos(n\Delta\phi) \right). \quad (4)$$

In earlier work [5, 6], we have investigated the p_T and path length (L) dependence of jet quenching via the scaling properties of $R_{AA}(p_T, L)$. The observed scaling indicated a decrease of $R_{AA}(p_T, L)$ with L and an increase of $R_{AA}(p_T, L)$ with $1/\sqrt{p_T}$. These trends were shown to be compatible with an energy loss mechanism dominated by medium induced gluon radiation [4];

$$R_{AA}(p_T, L) \simeq \exp \left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q} \frac{\mathcal{L}}{p_T}} \right] \\ \mathcal{L} \equiv \frac{d}{d \ln p_T} \ln \left[\frac{d\sigma_{pp}}{dp_T^2}(p_T) \right], \quad (5)$$

where α_s is the strong coupling constant, C_F is the color factor and \hat{q} is the transport coefficient which characterizes the squared average transverse momentum exchange [per unit path length] between the medium and the parton. An estimate of \hat{q} was also extracted from the scaling

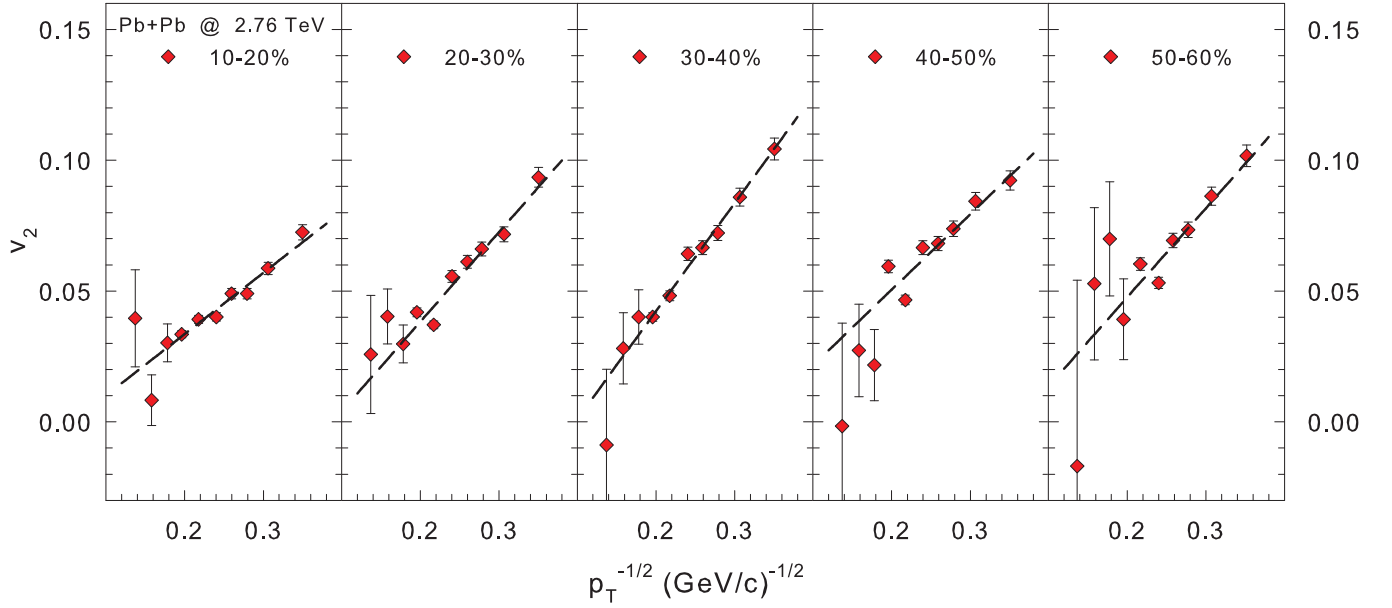


FIG. 1. (Color online) $v_2(p_T)$ vs. $1/\sqrt{p_T}$ for several centrality selections as indicated. Error bars are statistical only. The data are taken from Refs. [27, 28]. The dashed curve in each panel is a linear fit to the data.

curves. If jet quenching serves as a driver for azimuthal anisotropy, scaling as a function of p_T and $\Delta L = L_y - L_x$ (the difference between the out-of-plane (y) and in-plane (x) path lengths) might be expected. Thus, it is important to investigate whether azimuthal anisotropy measurements show complimentary scaling patterns which reflect the underlying energy loss mechanism suggested by the R_{AA} measurements.

In this work, we use high- p_T v_2 data to search for these scaling patterns, with an eye toward an independent estimate of \hat{q} . The observation of such patterns could also serve as a confirmation that at high- p_T , R_{AA} and v_2 stem from the same energy loss mechanism, and this mechanism is dominated by medium induced gluon radiation.

The high- p_T ($p_T \gtrsim 8$ GeV/c, $1 < |\eta| < 2$) measurements employed in our search were recently reported for charged hadrons by the CMS and ATLAS collaborations [27, 28]. These data indicate an increase of $v_2(p_T)$ from central to mid-central collisions, as might be expected from an increase in ΔL as collisions become more peripheral. They also indicate a characteristic decrease of v_2 with p_T , suggestive of a $1/\sqrt{p_T}$ dependence. These key features are important to the scaling search discussed below.

To facilitate comparisons to our earlier scaling analysis of R_{AA} data, we use the transverse size of the system \bar{R} as an estimate for the path length L , as was done in our earlier analyses [5, 6]. A Monte-Carlo Glauber-based model calculation [8, 9] was used to evaluate the values for \bar{R} and the eccentricity ε in Pb+Pb collisions as follows. For each centrality selection, the number of participant nucleons N_{part} , was first estimated. Sub-

sequently, \bar{R} and the eccentricity ε , were determined from the distribution of these nucleons in the transverse (x, y) plane as: $1/\bar{R} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$, and $\varepsilon = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$, where σ_x and σ_y are the respective root-mean-square widths of the density distributions. We use the estimate $\Delta L \equiv L_y - L_x = \varepsilon(L_x + L_y) \sim \varepsilon\bar{R}$ for the path length difference. Note that $L_y = (\sigma_x\sqrt{1+\varepsilon})/(1-\varepsilon)$ and $L_x = (\sigma_x\sqrt{1+\varepsilon})/(1+\varepsilon)$. For these calculations, the initial entropy profile in the transverse plane was assumed to be proportional to a linear combination of the number density of participants and binary collisions [29, 30]. The latter assures that the entropy density weighting used, is constrained by the Pb+Pb hadron multiplicity measurements [31]. Averaging for each centrality, was performed over the configurations generated in the simulated collisions.

Figure 1 shows the plots of $v_2(p_T)$ vs. $1/\sqrt{p_T}$ for several centrality selections as indicated. The dashed curves which represent a linear fit, indicates that within errors, $v_2(p_T)$ decreases as $1/\sqrt{p_T}$. This trend is opposite to the trend for $R_{AA}(p_T)$, and is to be expected if the anisotropy characterized by $v_2(p_T)$ stems from jet quenching (cf. Eq. 5), *i.e.* an increase in $R_{AA}(p_T)$ results in a corresponding decrease in $v_2(p_T)$.

The combined effects of $1/\sqrt{p_T}$ and ΔL scaling are demonstrated in Fig. 2. The left panel (a) of the figure shows the same linear dependence on $1/\sqrt{p_T}$ evidenced in Fig. 1, but with a different magnitude for each of the centrality selections indicated. The right panel (b) shows that, when the same data [shown in (a)] is scaled by ΔL , a single curve is obtained. The implied linear increase

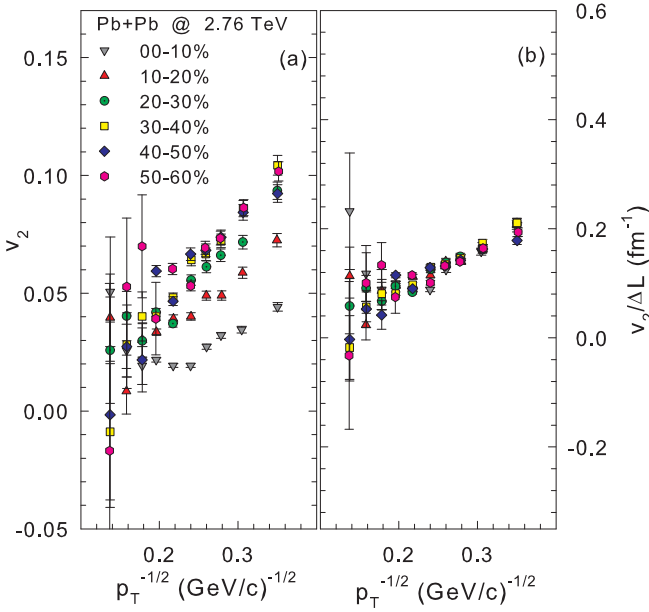


FIG. 2. (Color online) (a) $v_2(p_T)$ vs. $1/\sqrt{p_T}$ for the centrality selections indicated. (b) $v_2(p_T)/\Delta L$ vs. $1/\sqrt{p_T}$ for the same centrality selections. Error bars are statistical only.

of $v_2(p_T)$ with ΔL is complementary to the previously observed L dependence of jet quenching [5, 6]. That is, an increase in the effective path length L (ΔL) leads to more quenching (anisotropy). An extrapolation to higher values of p_T , of a linear fit to the data in Fig. 2(b), suggests that the anisotropy associated with jet quenching is negligible ($v_2 \sim 0$) for $p_T \gtrsim 100$ GeV. This is probably due to the relatively small magnitudes of ΔL . Note that for a fixed value of p_T , $\ln(R_{AA}(p_T, L))$ shows a linear dependence on L [5, 6].

For a given centrality, the azimuthal angle dependence of jet quenching [relative to the Ψ_2 event plane] $R_{AA}(\Delta\phi, p_T)$, is related to $v_2(p_T)$. This stems from the fact that the number of particles emitted relative to Ψ_2 , $N(\Delta\phi, p_T) \propto [1 + 2v_2(p_T) \cos(2\Delta\phi)]$. The anisotropy factor

$$R_{v_2}(p_T, \Delta L) = \frac{R_{AA}(90^\circ, p_T)}{R_{AA}(0^\circ, p_T)} = \frac{1 - 2v_2(p_T)}{1 + 2v_2(p_T)}, \quad (6)$$

(i.e. the ratio of the out-of-plane yield ($\Delta\phi = 90^\circ$) to in-plane yield ($\Delta\phi = 0^\circ$)), quantifies the magnitude of the quenching for path length difference ΔL . Therefore, the values of $R_{v_2}(p_T, \Delta L)$ can be used in concert with Eq. 5 to extract an estimate of \hat{q} .

To facilitate this estimate we first plot $\ln(R_{v_2}(p_T))$ vs. $1/\sqrt{p_T}$ for each centrality selection, as shown in Fig. 3. The dashed curve in each panel of the figure, represents a linear fit to the data; they show the expected linear dependence on $1/\sqrt{p_T}$ predicted by Eq. 5. The slopes S_{p_T} of these curves encode the magnitude of both α_s and \hat{q} .

For a given medium (fixed $\langle\hat{q}\rangle$) Eq. 5 suggests that the ratio $S_{p_T}/\Delta L$ should be independent of the collision centrality. This independence is indicated by the relatively flat centrality dependence for $S_{p_T}/\Delta L$, shown in Fig. 4. This observation serves as a further validation of Eq. 5, so we use the average value of these ratios $\sim 3.0 \pm 0.3$ GeV $^{1/2}$ /fm in concert with Eq. 5, to obtain the estimate $\hat{q}_{LHC} \approx 0.47 \pm 0.09$ GeV 2 /fm with values of $\alpha_s = 0.3$ [11], $C_F = 9/4$ [4, 32] and $\mathcal{L} = n = 6.7$ [33]. This estimate of \hat{q}_{LHC} , which can be interpreted as a space-time average, is similar to our earlier estimate $\hat{q}_{LHC} \approx 0.56 \pm 0.05$ GeV 2 /fm from scaled R_{AA} data, evaluated with the same values for C_F and α_s [6]. We conclude that radiative parton energy loss drives jet suppression and a collateral azimuthal anisotropy (v_2) develops, due to the difference in the in-medium parton propagation length (ΔL) in- and out of the Ψ_2 event plane.

In summary, we have performed scaling tests on the v_2 values obtained from azimuthal anisotropy measurements of high- p_T charged hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. v_2 shows a linear decrease as $1/\sqrt{p_T}$ and a linear increase with the medium path length difference (ΔL) in the directions parallel and perpendicular to the Ψ_2 event plane. These patterns, which are similar to the scaling patterns for jet quenching measurements ($\ln(R_{AA})$), confirm the $1/\sqrt{p_T}$ dependence, as well as the linear dependence on path length predicted by Dokshitzer and Kharzeev for jet suppression dominated by the mechanism of medium-induced gluon radiation in a hot and dense QGP. These observations also suggest that, at high- p_T , v_2 stems from jet quenching, and is a direct consequence of the difference in the parton propagation length ΔL . A simple estimate of the transport coefficient \hat{q} from the scaled v_2 data, gives a value which is similar to the value obtained in a prior study of the scaling properties of R_{AA} [6]. These results confirm that high- p_T azimuthal anisotropy measurements, provide strong additional constraints for delineating the mechanism(s) for parton energy loss, as well as for reliable extraction of \hat{q} .

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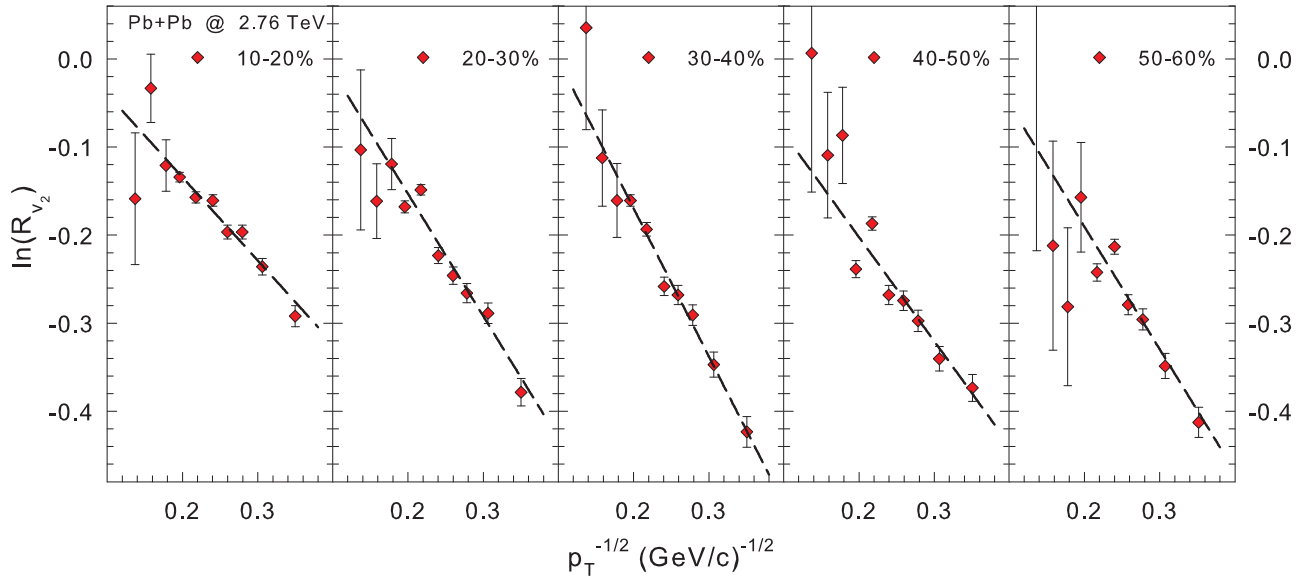


FIG. 3. (Color online) $\ln[R_{v_2}(p_T, \Delta L)]$ vs. $1/\sqrt{p_T}$ for several centrality selections as indicated. Error bars are statistical only. The dashed curve in each panel shows a linear fit to the data (see text).

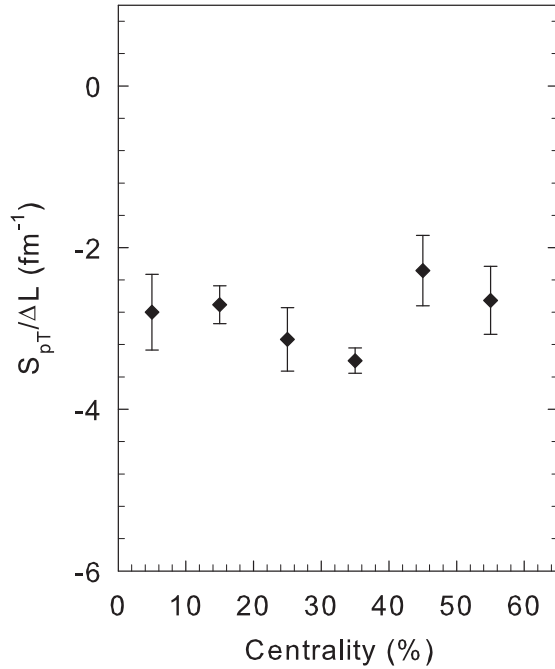


FIG. 4. (Color online) Centrality dependence of $S_{p_T}/\Delta L$, see text. The slopes S_{p_T} are obtained from the linear fits shown in Fig. 3.

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